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~~Method and Apparatus for Narrow-Band~~ Disturbance Signal Reduction in Servo Systems~~Positioning Signals~~

b~~B~~y

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Related Application

This application claims p~~P~~riority ~~is claimed~~ from U.S. Provisional Application Serial No. 60/394,854~~,~~ entitled "Narrow-Band NRRO Reduction Using a Non-linear Filter"~~,~~ filed on July 10, 2002~~,~~ which is incorporated herein by reference.

Field of the Invention

The present invention relates to reducing position~~ing~~ errors due to ~~random~~ disturbances in servo system~~mechanisms~~ and, in particular, to reducing ~~non-repeatable run-out (NRRO) due to narrow-band~~ disturbance signals in disk drive servo systems.

Background of the Invention

~~Background for the present invention is provided herein in connection with a disk drive servo system. It should be noted, however, that the present invention is not intended to be limited to such systems.~~

A disk drive is a data storage device that stores servo and user data in substantially concentric tracks on a data storage disk. During disk drive operation, the ~~data storage~~ disk is rotated about an axis while a transducer ~~is used to~~ reads data from and/or writes data to a target track of the disk. A servo ~~control~~ loop ~~is used to~~ positions the transducer above the target track while the data transfer occurs~~is taking place~~. The servo ~~control~~ loop uses servo data read from ~~a surface of~~ the ~~data storage~~ disk as position feedback to maintain the transducer in a substantially centered position above the target track~~ that is dictated by the mechanical properties of the disk drive~~.

The~~ypically,~~ servo data includes magnetic flux transitions~~,~~ such that when the transducer passes over the flux transitions~~,~~ the transducer generates a read~~-back~~ signal. The read~~-back~~ signal can be demodulated and decoded to provide a position error signal ~~(PES)~~ that indicates the position of the transducer relative to a track. The position error~~PES~~ signal is used by~~s utilized to~~ ~~generate an input signal for~~ the ~~head positioning~~ servo -loop to correct the position of the transducer relative to the track~~, as necessary~~.

D~~However, certain type of d~~isturbances in the disk drive can increase position~~ing~~ errors by ~~,~~ introducing disturbance signals into the position error signal. -Such disturbances can have a variable amplitude at a very narrow frequency band. For ~~An~~ example, ~~random disturbance can be~~ non-repeatable run out (NRRO) is a random disturbance due to a ~~disk~~ rocking mode~~,~~ ~~which is~~ excited by imperfections of balls in the

disk drive spindle motor bearing. The ~~range of the~~ disturbance amplitude varies from disk drive to disk drive and from time to time.

A~~Therefore, a~~ttempts have been made to reduce the position error in~~attenuate a portion of~~ the position error~~PES~~ signal~~s~~ that is ~~are~~ due to disturbances such as NRRO. -In one conventional approach, a notch filter ~~is adopted to~~ attenuates narrow-band disturbance signals in the position error signal~~PES~~. In order to provide adequate attenuation, the notch filter has a sharp and deep decrease in gain around the frequency of the disturbance. The amount of notch is determined empirically. However, this approach has a number of drawbacks. First, there is always a fixed level of attenuation regardless of the disturbance level, which can vary significantly. Further, the disturbance may not occur in all disk drives, and not all the time. For example, there may be more disturbance due to temperature rise~~,~~ or ~~due to~~ other excitation effect/force. A conventional~~,~~ linear disturbance signal_-attenuator~~,~~ ~~which~~ uses a notch filter~~,~~ to attenuate~~s~~ the disturbance signal even if there is no, or minimal, disturbance. This increases position error and lowers performance.

Further, ~~using~~ a notch filter affects the error transfer function over~~n~~ the entire frequency range. _(The error transfer function is the frequency response that determines the position error.) Because the resulting error transfer function is distorted by the notch filter from its highly optimized original shape, the performance is worse if the targeted disturbance is not present in the position error signal~~PES~~. Additionally, the fixed (linear) notch filter causes "ringing" ~~problems~~ in the steady-state response due to the exaggerated frequency response at the notch frequency.

As a compromise, ~~in~~ some conventional servo controllers use~~,~~ a notch filter with very weak attenuation (~~,~~around 3dB)~~, is utilized~~. However, weak attenuation is in~~not~~ sufficient when the disturbance is large. A~~Using a~~ notch filter for attenuating disturbances is further complicated because the notch frequency can fall on a phase cross-over frequency, where robustness constraints severely limit notch design.

Another conventional approach ~~involves~~ uses ~~of~~ a state estimator with ~~that utilizes~~ an internal model principle to estimate ~~the disturbance in~~ a torque disturbance form. The estimator is based on Kalman filter theory, requiring that statistical characteristics be known *a priori* to design the filter. However, ~~As~~ this is also a linear system that~~, it~~ suffers from similar problems as ~~mentioned in relation to~~ the notch filter. Such a linear system deteriorates the performance of the servo controller~~,~~ if the target disturbance is very small or not present.

Accordingly, there is a need for ~~a method and apparatus to~~ reducinge the positioni~~ng~~ error in a position error signal~~the PES~~ due to ~~the~~ narrow-band disturbances that introduces a disturbance signal in the position error signal~~PES,~~ while maintaining ~~the performance of the~~ servo controller ~~in terms of positioning performance and settling after seek~~performance.

~~Brief~~ Summary of the Invention

The present invention addresses the above needs.

T~~In one embodiment, t~~he present invention provides ~~a method for operating~~ a servo system that includes a first member and a second member that is positionable relative to the first member~~ in response to position signals~~. A position error signal ~~is~~

~~generated to~~ causes the second member to be positioned at~~to~~ a desired location relative to the first member. Disturbances in the servo-system introduce disturbance signals into the position error signal and p~~. According to an embodiment of the present invention, p~~osition~~ing~~ errors due to the~~such~~ disturbance signals are reduced by non-linear attenuation.

An embodiment ~~In one example, this~~ includes ~~the steps of~~ selectively varying a disturbance signal in the position error signal as a function of the amplitude~~magnitude~~ of the disturbance signal. ~~As such, the level of the disturbance signal varies as a non-linear function of the magnitude of the disturbance signal.~~

Another embodiment ~~of the above method~~ includes ~~the steps of:~~ filtering the position error signal to selectively pass the disturbance signal,~~;~~ generating a correction signal having an amplitude~~magnitude~~ that varies as a non-linear function of the amplitude~~magnitude~~ of the disturbance signal,~~;~~ and combining the correction signal with the position error signal to generate a corrected position error signal for a servo~~position~~ controller, thereby enabling the servo~~position~~ controller to selectively react to the disturbance with varying amplitude.

F~~The step of f~~iltering the position error signal may include~~further comprise the steps of:~~ determining the frequency band of the disturbance signal and filtering the position error signal using a peak filter to selectively pass the disturbance signal. In another case, ~~the step of~~ filtering the position error signal includes ~~the steps of~~ determining the frequency band and amplitude~~magnitude~~ range of the disturbance signal, and filtering the position error signal using a peak filter based on the frequency band and

amplitude~~magnitude~~ range of the disturbance signal to selectively pass the disturbance signal.

Another embodiment ~~In an example implementation of the above method, the present invention~~ provides a servo system having a servo~~control~~ loop that includ~~ing:~~es a servo controller that generates a position error signal ~~coupled to said second member~~ causing the~~said~~ second member to be positioned at~~to~~ a desired location relative to the~~said~~ first member,~~;~~ and an attenuator that selectively reduces position~~ing~~ errors due to disturbances by non-linear attenuation.

~~As noted, disturbances in the servo system introduce disturbance signals into the position signal.~~ The attenuator includes a gain controller that selectively varies ~~(e.g., amplifies or attenuates)~~ a disturbance signal in the position error signal~~,~~ as a non-linear function of the ampl~~magn~~itude of the disturbance signal.

-In one version~~example~~, the gain controller selectively amplifies or attenuates~~provides varying amplification/attenuation of~~ the disturbance signal such that reduction of position~~ing~~ errors increases as a non-linear function of the ampl~~magn~~itude of the disturbance signal.

In another version, the attenuator includes~~:~~ a peak filter that filters the position error signal to selectively pass the disturbance signal,~~;~~ a gain controller that generates a correction signal having an ampl~~magn~~itude that varies as a non-linear function of the ampl~~magn~~itude of the disturbance signal,~~;~~ and a combiner that combines the correction signal with the position error signal to generate a corrected position error signal for the~~a~~ servo~~position~~ controller, thereby enabling the servo~~position~~ controller to selectively react

to disturbances having varying amplitudes.-_The~~ filter comprises a~~ peak filter is ~~selected~~ based on the frequency band of the disturbance signal.

In yet another version of the servo system, the position error signal includes multiple peaks at different frequencies, and the attenuator includes~~:~~ a first filter that filters the position error signal to selectively pass a first disturbance signal at a first peak frequency,~~;~~ a first gain controller that generates a first correction signal having an ampl~~magn~~itude that varies as a non-linear function of the ampl~~magn~~itude of the~~said~~ first disturbance signal~~ at the first peak frequency,~~~~;~~ a second filter that filters the position error signal to selectively pass a second disturbance signal at a second peak frequency,~~;~~ a second gain controller that generates a second correction signal having an ampl~~magn~~itude that varies as a non-linear function of the ampl~~magn~~itude of the~~said~~ second disturbance signal~~ at the second peak frequency,~~~~;~~ and a combiner that combines the first and/or the second correction signals with the position error signal to generate a corrected position error signal with selectively varied disturbance signals in a non-linear manner.

Each attenuator can include~~further comprise:~~ a saturation controller that controls the output signal~~of the filter~~ to preserve servo_-loop stability if~~as~~ the gain controller output increases above a threshold, and a deadzone controller that controls the output signal~~of the filter~~ to maintain ~~improved performance of the~~ servo~~position~~ controller performance if the amplitude of the disturbance signal decrease~~is~~ below a threshold.

Other objects, embodiments, features and advantages of the invention will be apparent from the following descrip~~specifica~~tion taken in conjunction with the following drawings.

Brief Description of the Drawings

Figure 1 shows ~~an example block diagram of certain functional components of an embodiment of~~ a disk drive that implementin~~g aspects~~s ~~of~~ the present invention;

Figure 2 shows ~~an example functional arrangement of~~ an attenuator for non-linear filtering of a narrow-band disturbance signal~~s~~ in a~~the~~ position~~ing~~ error signal ~~(PES)~~ of the disk drive ~~of Figure 1, according to an embodiment of the present invention~~;

Figures 3A-3B show ampl~~magn~~itude and phase plots, respectively, of the frequency response of a band pass~~an example peak~~ filter in the attenuator~~the arrangement of Figure 2~~;

Figure 4 shows a decomposition plot for the position error signal~~PES~~ where ~~including~~ a disturbance signal due to a rocking mode of the disk drive is unattenuated;

Figure 5 shows a decomposition plot for the position error signal~~PES plot of Figure 4,~~ where~~in~~ a~~the~~ disturbance signal due to a rocking mode of the disk drive is ~~has been~~ attenuated ~~by the arrangement in Figure 2~~;

Figure 6 shows the attenuator with a saturation controller and a deadzone controller~~an example functional arrangement of non-linear filtering for attenuating narrow-band disturbance signals in the disk drive of Figure 1, according to another embodiment of the present invention~~; and

Figure 7 shows the attenuator with multiple ~~an example functional block diagram of a non-linear~~ filter~~ing~~ branches~~bank according to yet another embodiment of the present invention~~.

Detailed Description of the Invention

While this invention is susceptible of embodiments in many different forms, the preferred embodiments ~~y~~ are shown in the drawings and will ~~herein~~ be described in detail, ~~preferred embodiments of the invention~~ with the understanding that the present disclosure is ~~to be considered as~~ an exemplification of the principles of the invention and is not intended to limit the broad aspects of the invention to the embodiments illustrated. ~~Further, although example embodiments of the present invention are described in connection with a disk drive servo system, it should be noted that the present invention is not intended to be limited to disk drive systems.~~

Figure 1 illustrates ~~an example~~ disk drive ~~system~~ 100 implementing aspects of the present invention. The disk drive ~~system~~ 100 ~~is operative for~~ performs~~ing~~ data storage and retrieval functions for an external host computer 102. The disk drive ~~system~~ 100 includes~~:~~ -a data storage disk 104, a transducer 106, an actuator assembly 108, a voice coil motor (VCM) 110, a read/write channel 112, an encoder/decoder (ENDEC) 114, an error correction coding (ECC) unit 116, a data buffer ~~memory~~ 118, an interface ~~unit~~ 120, a servo controller 122~~,~~ and a disk controller~~/microprocessor~~ 124.

In general, the disk 104 includes one or two disk surfaces (not shown) which are coated with ~~a~~ magnetic material ~~that is~~ capable of changing its magnetic orientation in response to an applied magnetic field. Data is stored digitally in ~~the form of~~ magnetic polarity transitions (frequently referred to as pulses in cells) within concentric tracks on ~~one or more of~~ the disk surface(s). The disk 104 is rotated at a substantially constant spin rate by a spindle motor (not shown) that is speed-controlled by a closed-loop feedback system. Instead of the single disk 104 ~~shown in **Figure 1**~~, the disk drive~~system~~ 100 can

include multiple~~a plurality of~~ disks 104 each ~~all~~ mounted on a single spindle and ~~each~~ serviced by one or more separate transducers 106.

The transducer 106 ~~is a device that~~ transfers information to and from~~/to~~ the disk 104 during read and write operations. The transducer 106 is positioned over the disk 104~~,~~ ~~typically,~~ by the~~a rotary~~ actuator assembly 108 that pivots about an axis under the power of the VCM 110. During a write operation, a polarity-switchable write current is delivered to the transducer 106 from the ~~read/write~~ channel 112 to induce magnetic polarity transitions onto a desired track of the disk 104. During a read operation, the transducer 106 senses magnetic polarity transitions on a desired track of the disk 104 to create an analog read signal that is indicative of the data stored thereon. T~~Commonly, t~~he transducer 106 is commonly a dual element head having a magneto-resistive read element and an inductive write element.

The VCM 110 receives movement commands from the servo controller 122 for properly positioning the transducer 106 above a desired track of the disk 104 during read and write operations. The servo controller 122 is part of a servo~~feedback~~ loop that uses servo information from ~~the surface of~~ the disk 104 to control the movement of the transducer 106 and the actuator assembly 108 in response to commands from the disk controller~~/microprocessor~~ 124. T~~A function of t~~he servo controller 122 ~~is to~~ minimizes tracking errors.

During a read operation, the channel 112 receives the ~~analog~~ read~~-back~~ signal from the transducer 106 and processes the read signal to create ~~a~~ digital data ~~read signal~~ representative of the data stored on the disk 104. The channel 112 t~~T~~ypically includes~~,~~ detection circuitry and ~~is included in the channel 112. The channel 112~~ ~~may also include~~

a read clock ~~means~~ for deriving timing information~~, such as a read clock,~~ from the read~~analog~~ signal.

The disk controller~~/microprocessor~~ 124 is a microprocessor that ~~operative for~~ controls~~ling~~ the operation and timing of ~~the~~ other components in ~~elements of~~ the disk drive~~system~~ 100. In addition, the disk controller~~/microprocessor~~ 124 may perform the functions of some of these components~~elements of the system~~. For example, the disk controller~~/microprocessor~~ 124 may perform ~~some~~ computation ~~functions~~ for the servo controller 122.

The transducer 106 generates a read signal in response to s~~Positioning~~ servo data~~bursts~~ on the disk 104 and the ~~induce analog~~ read signal~~s~~ is converted by an analog-to-digital converter in ~~in the transducer 106 that are processed through~~ the channel 112~~.~~ ~~The channel 112 includes an analog to digital converter (ADC) to convert the analog servo burst signals~~ into digital data ~~values~~ representing the amplitudes of the read ~~analog~~ signals. The servo controller 122 and/or the disk controller 124 demodulates~~further processes~~ the digital data to determine ~~transducer~~ position information for the transducer 106 and provides servo control signals to the VCM 110 for positioning the transducer 106 during seek~~ing~~ and on-track operations. Thus~~As such~~, in a servo-loop ~~system is formed such that~~ the VCM 110 moves the transducer 106 and the actuator assembly 108 ~~and transducer 106~~ in response to the~~said~~ servo burst~~control input signal~~s.

~~In one example, servo burst information is read by the transducer 106 from the disk 104. The servo controller 122 and/or the disk controller 124 provide demodulation for processing the digital servo data from the channel 112, and generate transducer/head position information including a position error signal (PES). The servo controller 122~~

~~provides control signals to the VCM 110 for positioning the transducer 106 (e.g., seeking to a target track, tracking over a target track, etc.).~~

After a seek operation to a target track, the servo loop ~~data is~~ uses~~d~~ ~~by~~ the servo data ~~loop~~ to generate a position error signal to ~~for~~ maintain~~ing~~ ~~the position of~~ the transducer 106 over ~~relative to~~ the target ~~that~~ track during an on-track operation. ~~The PES signal is utilized to generate an input signal for the head positioning servo loop to correct the position of the transducer relative to the track as necessary.~~

D~~As noted, d~~isturbances in the servo -system introduce disturbance signals into the position error signal. Advantageously, ~~ccording to an embodiment of the present invention,~~ the servo controller 122 ~~implements a method for~~ attenuates~~ing~~ position~~ing~~ errors due to narrow-band disturbances in the ~~disk drive~~ position error signal ~~(e.g., PES)~~.

–**Figure 2** shows an attenuator 200 for non-linear filtering of a narrow-band disturbance signal in a position error signal of the disk drive 100. In other words, the attenuator 200 ~~an example functional block diagram of an embodiment of a non-linear filtering arrangement 200 in the servo controller 122, according to the present invention, for~~ attenuates~~ing~~ position~~ing~~ errors due to narrow-band disturbances in the position error signal~~PES~~.

The attenuator 200 is located in the servo controller 122 and ~~example nonlinear filtering arrangement 200 in **Figure 2**~~ includes a band pass filter ~~function~~ 202, ~~and~~ a ~~non-linear~~ gain controller ~~function~~ 204 and a combiner 206.

–The band pass filter 202 filters the position error signal~~PES~~ and passes the disturbance signal in the position error signal~~PES,~~ to the gain controller ~~function~~ 204.

The gain controller 204 performs ~~for selective~~ non-linear attenuation on the disturbance signal ~~variation~~and passes ~~, wherein the output of the gain function 204 is~~ a correction signal to the combiner 206. The combiner 206 combines the position error signal and the correction signal to provide ~~that is combined with the original PES signal in a combiner node 206 to generate~~ a corrected position error~~PES~~ signal.

~~In this example, the output of the gain function 204 is a non-linear value and the combiner node 206 is a summing node. The variable gain of the non-linear function 204 adjusts the level of position error attenuation in accordance with the strength of the disturbance causing the position error. The description below is provided in the context that the arrangement in **Figure 2** attenuates non-repeatable run out (NRRO) position errors in the PES.~~

The disturbance is NRRO that occurs in a rocking mode of the disk drive 100. The NRRO creates the position error in the position error signal as the disturbance signal in the position error signal.

T~~In this example,~~ the band pass filter 202 i~~comprise~~s a peak filter that passes only ~~designed to pass~~ a selected narrow-band frequency range ~~component~~ of the position error signal~~PES~~ that ~~only, wherein the narrow-band frequency~~ includes the disturbance signal ~~to be attenuated~~.

~~The filter 202 comprises a peak filter, and the frequency response of the peak filter 202 is selected based on the frequency range of the disturbance signal to be processed.~~

–The band pass filter 202 narrow-band frequency range is ~~In one example, the peak filter frequency can be~~ determined by examining the frequency range of the ~~target~~ disturbance. For example, the base frequency of the disturbance is determined by disk geometry, form factor, materials, components, etc. The disturbance frequency range is determined by industry standard measurements such as spectrum analysis software. Then the band pass filter 202 is designed using the industry standard measurements. As a result, the attenuator 200 is tuned for a particular disk drive product. Furthermore, the attenuator 200 can be tuned from disk drive to disk drive.

The gain controller 204 provides a non-linear gain function that adjusts the attenuation of the disturbance signal in response to the amplitude (magnitude) of the disturbance signal. Preferably, t~~**Figures 3A-B** show magnitude plot 208 and phase plot 210, respectively, of the frequency response of an example peak filter 202. This example peak filter 202 is designed for NRRO disturbance signals with the peak of about 2.5 on the linear scale, and frequency location/range at about 1.9 KHz.~~

~~Referring back to **Figure 2**, after the PES is filtered by the peak filter 202, the non-linear gain function 204 performs arithmetic operations on the filtered PES to output correction values to be combined with the PES. In one embodiment,~~ the non-linear gain function ~~204~~ is ~~comprises~~ an odd function ~~*f(u)*~~ where~~in~~ the product of positive and negative inputs is negative~~and output are always positive. The output values of the gain function 204 are added to the original PES signal by the summing node 206 in the arrangement 200 of **Figure 2** to attenuate the position error due to said disturbances, in the PES.~~

An example non-linear gain function ~~$f(u)$~~ is a cubic ~~gain~~ function~~,~~ $f(u)$ having ~~two~~ tunable parameters M, N~~,~~ according to the relation ~~(1) below~~:

$$f(u) = M\left(\frac{u}{N}\right)^3 \qquad (1)$$

The parameters M, N are~~can be~~ selected to signify the effect of the cubic function $f(u)$ ~~only~~ when there is a strong distu~~ru~~bance at the target disturbance frequency but not when there is a weak disturbance at the target disturbance frequency.

The parameter ~~value of~~ N is ~~selected~~ based on the ~~level/~~ampl~~magn~~itude of the ~~NRRO~~ disturbance signal (~~i.e.,~~ u) and is the threshold level of signal increase/decrease. I~~, so that i~~f the disturbance signal amplitude u is smaller than N~~,~~ then the ratio u/N is reduced when cubed. On the other hand, ~~but~~ if the disturbance signal amplitude u is greater than N then the ratio u/N is increased when cubed.

Thus~~As such~~, the cubic function $f(u)$ ~~filter can~~ selectively amplifies~~y~~ or attenuates the disturbance signal depending on the ratio u/N~~, to thereby attenuate the position error in the PES due to said narrow-band disturbances~~. Likewise, t~~By using~~ the cubic function $f(u)$ provides ~~fulter, there is~~ variable gain ~~on the peak filter~~ and ~~a~~ resulting variable attenuation of the position error signal~~PES~~.

The ~~effect of the~~ cubic ~~gain~~ function $f(u)$ ~~is~~ has several notable effects~~two-fold~~. First, the cubing operation redistributes the energy of the input signal by creating ~~the~~ third harmonics at ~~the~~ triple ~~of~~ the base frequency. Second, ~~due to cubing,~~ the ratio ~~of u to N (i.e.,~~ u/N~~)~~ is increased or decreased if the absolute value of u/N is larger or smaller than 1, respectively.

~~As such, the cubic function *f(u)* provides non-linear gain based on the magnitude of the NRRO disturbance signal, *u*.~~ The parameter *M* adjusts the overall amplification of the value $(u/N)^3$. Therefore, if the ~~target NRRO~~ disturbance signal is weak then~~,~~ the amplification by the cubic function *f(u)* is low~~,~~ and the disturbance signal has essentially no effect on the corrected position error signal or the servo system. That is, the corrected position error signal is essentially the position error signal. However, if the ~~NRRO~~ disturbance signal is strong then~~,~~ the amplification by the cubic function *f(u)* is high and the disturbance signal substantially effects the corrected position error signal~~. Stated differently, when the NRRO signal is weak, then the output of the non-linear gain function *f(u)* is small, and essentially does not affect the servo loop. However, if there is a substantial level of NRRO, then there is high amplification by the non-linear gain function *f(u)*~~. That is, the corrected position error signal differs substantially from the position error signal.

~~The output values of the non-linear gain function *f(u)*, when added to the original PES signal by the summing node 206 in the nonlinear filtering arrangement 200 of **Figure 2**, effectively adjust (vary) the attentuation level of the position error in the PES. As a result of that non-linear gain, the PES and settling performance is maintained when the disturbance signal amplitude is very small.~~

The ~~non-linear gain effect of the~~ cubic function *f(u)* has non-linear gain that is confined to a narrow frequency band due to the band pass ~~peak~~ filter 202. For ~~In one~~ example~~-application~~, in a ~~disk~~ rocking mode for the disk drive 100~~,~~ the third harmonics

~~(e.g.,~~ around 6 KHz~~)~~ are ~~significantly~~ attenuated by -40 dB/dec~~the lowpass filtering nature (e.g., -40 dB/dec) of the VCM dynamics~~.

The combiner 206 is a summing node.

Figures 3A-3B show an amplitude plot 208 and a phase plot 210, respectively, of the frequency response of the band pass filter 202. As is seen, the band pass filter 202 has a narrow-band frequency range at about 1.9 KHz.

Figure 4 shows a decomposition ~~n example Fourier Transform (FFT)~~ plot for ~~of~~ the position error signal~~PES~~ in the ~~a~~ disk drive 100 where the disturbance signal is unattenuated. The decomposition plot is ~~over~~ a ~~rocking mode frequency range, without any disturbance signal attenuation.~~ Fourier Transform of t~~-The~~ position error signal~~PES~~ that ~~decomposition shown in **Figure 4**~~ includes a ~~a~~ repeatable run out (RRO) disturbance signal ~~plot~~ 212 and an ~~a~~ NRRO disturbance signal ~~plot~~ 214. As is seen, the RRO disturbance signal 212 and the NRRO disturbance signal 214 are pronounced within the rocking mode frequency range at about 1.9 KHz.

Figure 5 shows a decomposition plot for the position error signal in the disk drive 100 where the disturbance signal is ~~an FFT plot (similar to that of **Figure 4**), wherein the disturbance signal 214 has been~~ attenuated by the attenuator ~~non-linear filtering arrangement~~ 200 ~~of **Figure 2**, over the rocking mode frequency range, according to the present invention~~. The decomposition plot is a Fourier Transform of the position error signal that includes the RRO disturbance signal 212 and the NRRO disturbance signal 214. As is seen, the attenuator ~~The non-linear filtering arrangement~~ 200 provides selective attenuation~~variation~~ of the RRO disturbance signal 212 and the NRRO disturbance signal 214 over the ~~selected~~ rocking mode frequency range~~,~~ at about 1.9 KHz

and therefore improves the ~~overall~~ position error signal~~PES~~ when the target disturbance is present.~~ It does so while maintaining PES performance when target disturbance is not present, and preserves settling performance regardless of the presence of a target disturbance.~~

~~The non-linear gain function *f(u)* for automatic attenuation level adjustment depends on the disturbance magnitude. As such, in relation (1) above, the value *N* is selected as the threshold level of signal increase/decrease, and the value *M* is selected for setting the overall gain. Accordingly, the present invention provides combined usage of non-linear gain and narrow-band peak filter to confine the non-linear effect in a predetermined frequency. The disturbance signal is selectively varied (e.g., attenuated/amplified) by the non-linear function.~~

~~The frequency response of the peak filter 202 can be selected by experimentation based on the frequency range of the disturbance signal to be varied (adjusted). The spectrum shown in **Figure 5** is different from disk drive to disk drive. In one example, the base frequency is 2 KHz, and is determined by manufacturing and disk geometry such as form factor, materials, components, etc. As such, the non-linear filtering arrangement is tuned for a particular type of disk drive product. Identification of the NRRO disturbance frequency range can be determined using industry standard measurements, such as spectrum analysis software. Then, the peak filter 202 may be designed accordingly using the industry standard measurements.~~

Figure 6 shows an attenuator ~~example non-linear filtering arrangement~~ 300 for non-linear filtering of a narrow-band disturbance signal in a position error signal of the disk drive 100~~according to another embodiment of the present invention~~.

______–The attenuator 300 ~~example non-linear filter arrangement 300~~ includes a band pass filter 302, an optional saturation controller ~~block~~ 304, a ~~non-linear~~ gain controller~~function~~ 306, an optional deadzone controller~~block~~ 308 and a combiner ~~node~~ 310.~~ The optional saturation and deadzone blocks 304, 308, respectively, can be placed in a different order than that shown in **Figure 6**.~~

The band pass filter 302, the ~~non-linear~~ gain controller ~~function~~ 306~~,~~ and the combiner ~~node~~ 310 are~~, operate in a~~ similar to ~~manner as~~ the band pass filter 202, the ~~non-linear~~ gain controller~~function~~ 204 and the combinder ~~node~~ 206, respectively~~, described above in relation to **Figure 2**~~.

The saturation contoller~~block~~ 304 preserv~~otecte~~s ~~the~~ servo-loop stability by limit~~controll~~ing the output of the attenuator~~non-linear filter arrangement~~ 300, which may grow very large due to the ~~non-linear~~ cubic ~~gain~~ function ~~306,~~ *f(u)*~~.~~ provided by the gain controller 306. Thus~~For example~~, the saturation controller~~block~~ 304 ~~may include a limiter, that~~ limits the effect~~action~~ of the cubic ~~gain~~ function *f(u)* ~~306,~~ to maintain servo loop stability. The saturation controller ~~block~~ 304 imposes upper and lower limit~~bound~~s on an~~the~~ input signal. If~~When~~ the input signal is within the ~~range specified by~~ upper and ~~a~~ lower limits then~~and an upper limit,~~ the input signal passes through the saturation controller 304 unchanged. However, if~~When~~ the input signal is outside the upper and lower limits then the saturation controller 304 clips the input~~these limits, the~~ signal ~~is~~

~~clipped~~ to the upper or lower limits. The saturation controller~~block~~ 304 can be implemented as an ASIC, firmware, program instructions for execution by a CPU, etc.

~~Further, t~~The deadzone controller~~gain block 308~~ 308 preserves the position error signal by eliminating~~es~~ the ~~cubic~~ effect of the cubic function *f(u)* when the target disturbance is very small. Thus,~~e~~ the deadzone controller 308 ~~deadzone, created by the integer division of fixed-point digital signal processing,~~ blocks the effect of the cubic function *f(u)*~~effect~~ if the target disturbance is neglible~~, hence preserving the original PES performance intact~~. The deadzone controller 308 creates a deadzone (region of zero output) by integer division of fixed-point digital signal processing. ~~In one example, the deadzone block 308 defines a region of zero output.~~ If the input signal ~~of the deadzone block 308~~ is within ~~a selected minimum and maximum (~~the deadzone then the~~), its~~ output signal is zero. However, if the input signal is outside the deadzone then the ~~Outside of this zone, its~~ output signal is a linear function of the input signal with a slope of 1. The deadzone controller~~block~~ 308 can be implemented as an ASIC, firmware, program instructions for execution by a CPU, etc.

The saturation controller 304 and the deadzone controller 308 can be placed in a different order than that shown in the attenuator 300.

Figure 7 shows an attenuator ~~example non-linear filtering bank arrangement~~ 400 for non-linear filtering of a narrow-band disturbance signal in a position error signal of the disk drive 100~~according to another embodiment of the present invention~~.

–The attenuator~~rrangement~~ 400 includes ~~multiple non-linear~~ filter branches 402a and~~,~~ 402b and a combiner 420~~ of the types shown by example in **Figures 2 and 6**. In cases where the NRRO disturbance signal has multiple peaks at different frequencies, the non-linear filtering bank arrangement 400 of **Figure 7** provides attenuation of the NRRO signal at the multiple peak frequencies. The first branch 402a includes a peak filter 404, a saturation block 406, a non-linear gain function 408 and a deadzone block 410. The second branch 402b includes a peak filter 412, a deadzone block 414, a non-linear gain function 416 and a saturation block 418. The correction value outputs of the branches 402a and 402b are combined with the original PES via the combiner node 420 to generate a corrected PES with reduced disturbance signals.~~

~~Preferably, the peak filter in each branch 402a, 402b, is at a different base frequency than the other peak filter. Further each branch 402a, 402b, can have a different non-linear gain function, and different optional saturation and deadzone blocks. The branches 402a, 402b can operate in parallel, or selectively in response to control signal based on the NRRO peaks.~~

~~According to another aspect of the present invention, the example non-linear filtering arrangements above can be activated when the servo controller enters the on-track mode (i.e., after a seek operation to a target track and while tracking the target track). By careful tuning through simulation, the transient response shows virtually no difference when the cubic function *f(u)* is operating.~~

~~As such, the present invention provides selective attenuation of the position error due to narrow-band disturbances in the PES by a non-linear gain function for automatic level adjustment of the disturbance signal in the PES depending on the disturbance signal magnitude. This provides combined usage of nonlinear gain and narrow-band peak filtering to confine the non-linear effect for a predetermined frequency. Further, in the example non-linear gain function of relation (1) above, the value *N* for the threshold level of signal amplification/attenuation, and the value *M* for setting the overall attenuation level, are selectable based on desired performance criteria.~~

~~As will be appreciated by those skilled in the art, in addition to the logic blocks shown in the drawings, the various methods and architectures described herein can be implemented as: computer instructions for execution by a microprocessor, as ASIC units, firmware, as logic circuits, etc. For example, the above steps and functions can reside as firmware in the servo controller (to be triggered on and off), or as a logic circuit in the disk drive controller.~~

~~The present invention has been described in considerable detail with reference to certain preferred versions thereof; however, other versions are possible. For example, although a cubic odd function is used in this embodiment, other odd functions such as a 5th-order odd function can also be used. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.~~ The filter branches 402a and 402b each receive the position error signal, and the

combiner 420 combines the position error signal with the correction signals from the filter branches 402a and 402b to generate the corrected position error signal.

The filter branch 402a includes a band pass filter 404, an optional saturation controller 406, a gain controller 408 and an optional deadzone controller 410 that are similar to the band pass filter 302, the saturation controller 304, the gain controller 306 and the deadzone controller 308, respectively. Likewise, the filter branch 402b includes a band pass filter 412, an optional deadzone controller 414, a gain controller 416 and an optional saturation controller 418 that are similar to the band pass filter 302, the deadzone controller 308, the gain controller 306 and the saturation controller 304, respectively. In addition, the combiner 420 is similar to the combiner 310.

The attenuator 400 attenuates the disturbance signal at multiple peak frequencies. For example, the band pass filters 404 and 412 have different base frequencies, the gain controllers 408 and 416 have different non-linear gain functions, the saturation controllers 406 and 418 are different and the deadzone controllers 410 and 414 are different. Further, the filter branches 402a and 402b can operate in parallel or operate selectively in response to the disturbance signal peaks.

The attenuators 200, 300 and 400 can generate the correction signals when the servo controller 122 enters on-track mode (after a seek to a target track and while tracking the target track). By careful tuning through simulation, the transient response shows virtually no difference when the cubic function *f(u)* is operating.

Advantageously, the present invention provides selective attenuation of the position error due to narrow-band disturbances in the position error signal by a non-linear gain function for automatic adjustment of the disturbance signal in the position error

signal depending on the disturbance signal amplitude. The combined non-linear gain and narrow-band peak filtering confine the non-linear effect to a predetermined frequency range. Further, in the cubic function *f(u)*, the parameter *N* for the threshold level of the disturbance signal amplification/attenuation and the parameter *M* for setting the overall attenuation level are selectable based on desired performance criteria.

As will be appreciated by those skilled in the art, in addition to the logic blocks shown in the drawings, the various methods and architectures described herein can be implemented as computer instructions for execution by a microprocessor, ASICs, firmware, logic circuits, etc. For example, the above steps and functions can reside as firmware in the servo controller 122 or as a logic circuit in the drive controller 124.

Although example embodiments of the present invention are described in connection with a disk drive servo system, it should be noted that the present invention is not limited to disk drives.

The present invention has been described in considerable detail with reference to certain preferred versions thereof, however other versions are possible. For example, although a cubic function has been described, other odd functions such as a 5^{th} order odd function can also be used. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

Abstract

A ~~method for operating a~~ servo system includes~~having~~ a first member and a second member that is positionable relative to the~~said~~ first member~~ in response to position signals~~. A ~~The~~ position error signals ~~are generated to~~ causes the~~said~~ second member to be positioned at a desired location relative to the first member. T~~In t~~he position error signal includes~~,~~ a position error due to a disturbance in the servo system, and the position error is reduced by ~~non-linear~~ attenuation of a ~~. Reducing the position error is performed by selectively adjusting the~~ disturbance signal as a non-linear function of the ampl~~magn~~itude of the disturbance signal.~~ Accordingly, attenuation of the disturbance signal increases as a non-linear function of the magnitude of the disturbance signal.~~